

Semi-Annual Technical Report

THE FLOW OF PLASMA IN THE SOLAR TERRESTRIAL ENVIRONMENT

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Grant: NAG5-1484

Period: 15 June 1991 - 31 March 1992

GODDARD
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P-21

(NASA-CR-190200) THE FLOW OF
PLASMA IN THE SOLAR TERRESTRIAL
ENVIRONMENT Semiannual Technical
Report, 15 Jun. 1991 - 31 Mar. 1992
(Utah State Univ.) 21 p

N92-31338

Unclass

G3/92 0083774

SPTP Accomplishments

In association with our NASA Theory Program, we have written 33 scientific papers and we have made 39 scientific presentations at both national and international meetings. Lists of the NASA Theory personnel, publications, and presentations are attached. In the paragraphs that follow, we outline the scientific goals of our program and then briefly highlight some of the papers we have submitted for publication within the last six months.

Scientific Goals

It has been clearly established, both experimentally and theoretically, that the various regions of the solar-terrestrial system are *strongly coupled*, that the coupling processes exhibit *time delays*, and that *feedback mechanisms* exist. For example, changes in the solar wind dynamic pressure and the interplanetary magnetic field affect the magnetospheric currents and electric fields, which, in turn, affect the ionospheric convection pattern, electron density morphology, and ion composition at high latitudes. The changes in the ionosphere then affect the thermospheric structure, circulation and temperature on a global scale. The changes in the ionosphere-thermosphere system then act to modify the magnetospheric processes. The variations in the ionospheric conductivities modify the magnetospheric electric fields and the large-scale current system linking the two regions. Additional feedback mechanisms occur in the polar cap via the 'polar wind' and in the auroral zone via 'energetic ion outflow', and these ionospheric ions are a significant source of mass, momentum and energy for the magnetosphere. However, all of the coupling and feedback mechanisms have time delays associated with them, which further complicates the situation.

With the above description in mind, the overall goal of our NASA Theory Program is to study the *coupling*, *time delays*, and *feedback mechanisms* between the various regions of the solar-terrestrial system in a *self-consistent*, *quantitative* manner. To accomplish this goal, it will eventually be necessary to have time-dependent macroscopic models of the different regions of the solar-terrestrial system and we are continually working toward this goal. However, our immediate emphasis is on the near-earth plasma environment, including the ionosphere, the plasmasphere, and the polar wind. In this area, we have developed *unique global models* that allows us to study the coupling between the different regions.

Another important aspect of our NASA Theory Program concerns the effect that localized 'structure' has on the macroscopic flow in the ionosphere, plasmasphere, thermosphere, and polar wind. The localized structure can be created by structured magnetospheric inputs (i.e., structured plasma convection, particle precipitation or Birkeland current patterns) or time variations in these inputs due to storms and substorms. Also, some of the plasma flows that we predict with our macroscopic models may be unstable, and another one of our goals is to examine the stability of our predicted flows.

Because time-dependent, three-dimensional numerical models of the solar-terrestrial environment generally require extensive computer resources, they are usually

based on relatively simple mathematical formulations (i.e., simple MHD or hydrodynamic formulations). Therefore, another long-range goal of our NASA Theory Program is to study the conditions under which various mathematical formulations can be applied to specific solar-terrestrial regions. This may involve a detailed comparison of kinetic, semi-kinetic, and hydrodynamic predictions for a given polar wind scenario or it may involve the comparison of a small-scale particle-in-cell (PIC) simulation of a plasma expansion event with a similar macroscopic expansion event. The different mathematical formulations have different strengths and weaknesses and a careful comparison of model predictions for similar geophysical situations will provide insight into when the various models can be used with confidence.

Ionosphere – Magnetosphere Coupling → Polar Cap Arcs

It is well known that the electric fields, particle precipitation, auroral conductivity enhancements, and Birkeland currents that couple the magnetosphere-ionosphere system are strongly dependent upon the direction of the interplanetary magnetic field (IMF). When the IMF is southward, the Birkeland currents flow in the Region 1 and 2 current sheets, the *F* region plasma convection exhibits a 2-cell structure with anti-sunward flow over the polar cap, and the auroral electron precipitation and ionospheric conductivity enhancements are confined to the statistical auroral oval. For this situation, empirical (statistical) models have been developed to describe the important magnetospheric parameters (field-aligned currents, electric fields, etc.) and these models have been used successfully to model ionospheric and thermospheric processes. In general, however, magnetospheric electric fields and particle precipitation exhibit a considerable amount of spatial (mesoscale) structure and this could have a significant effect on the ionosphere-thermosphere system. The structure is particularly evident during northward IMF, when multiple sun-aligned arcs can occur in the polar cap. Unfortunately, the convection electric field characteristics in and near sun-aligned arcs have not been fully elucidated and, hence, it is currently not possible to rigorously model the ionosphere-thermosphere coupling when sun-aligned arcs are present. In an effort to address this issue, a two-dimensional, time-dependent model of polar cap arcs was developed at USU in which the electrodynamics of the polar cap arc is treated self-consistently in the frame of the coupled magnetosphere-ionosphere (M-I) system (paper 30).

Figure 1 is a schematic overview showing the M-I framework for the polar cap arc model. Initially, a magnetospheric shear flow carried by Alfvén waves propagates towards the ionosphere. The downward propagating Alfvén waves can be partially reflected from the ionosphere, and then bounce around between the ionosphere and magnetosphere. The wave reflections depend on the conditions in the ionosphere and magnetosphere. The propagating Alfvén waves can carry both upward and downward field-aligned currents. The precipitating electrons associated with the upward field-aligned currents enhance the conductivity in the ionosphere, and at the same time, the change of the ionospheric conductivity can launch a secondary Alfvén wave towards the magnetosphere. The process is transient, during which all physical quantities in the ionosphere change self-consistently in time and polar cap arcs develop. Due to the finite conductivity in the ionosphere, the bouncing Alfvén waves in the coupled M-I system will eventually be damped, and the whole M-I system, as well as the development of the polar cap arcs, will approach an asymptotic steady state.

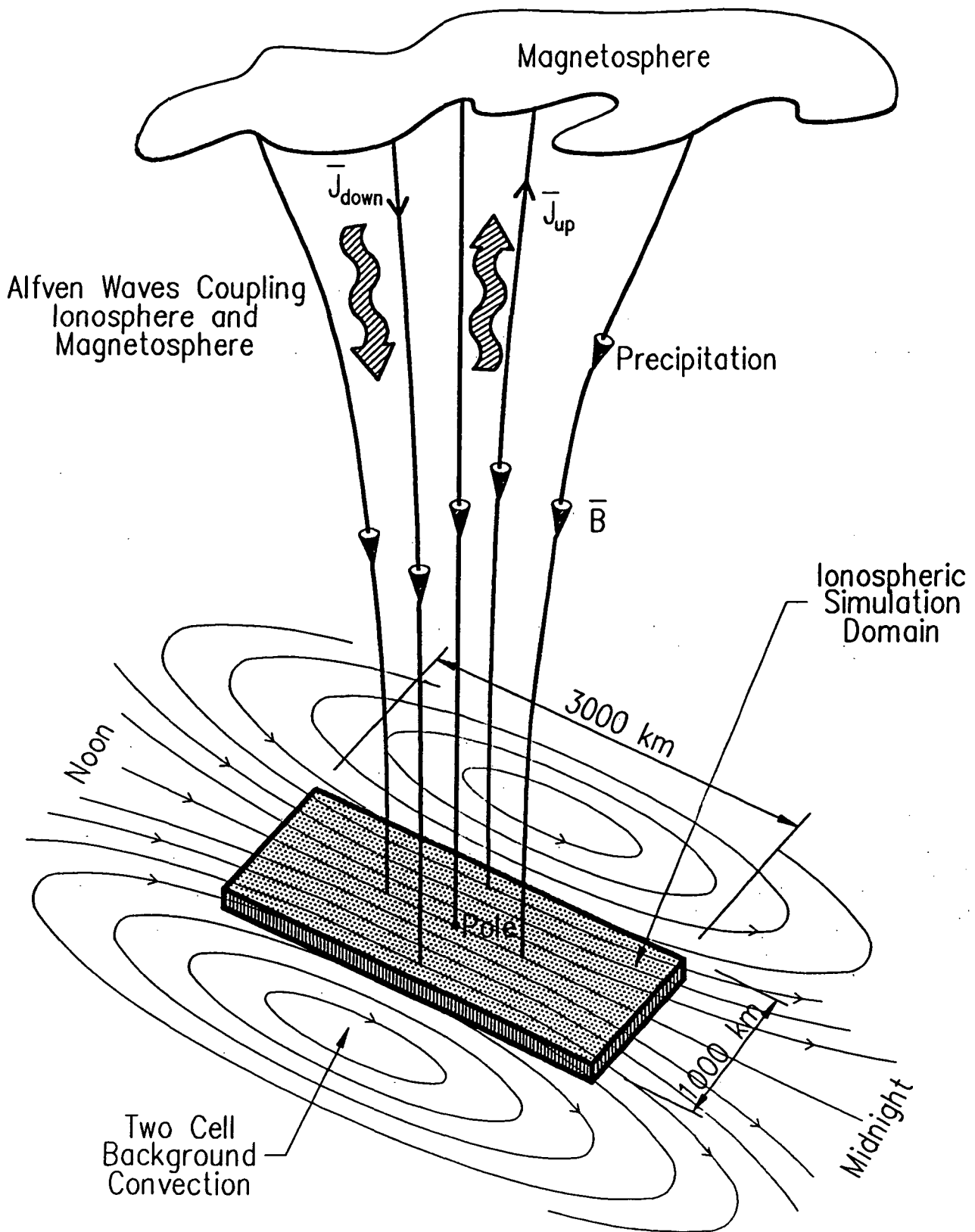


Fig. 1. Schematic diagram showing the geophysical framework of the polar cap arc model. The background ionospheric convection is for illustrative purposes only. The actual convection pattern is not necessarily a two-cell pattern. From paper 30.

The modelling results indicate that the time constant for the formation of polar cap arcs is around 10 minutes. It was found that an initial single arc precipitation pattern tends to split into multiple precipitation regions and leads to a multiple structure of the polar cap arc. It was also found that a strong downward field-aligned current can develop near the intense upward field-aligned current and form a pair structure of the field-aligned current in the polar cap arc. The model predicts the existence of plasma flow across the polar cap arc, but the amplitude of the flow is small and the characteristic time scale of it is much larger than the time constant for the formation of the polar cap arc. The results also show that when the polar cap arc approaches a steady state, almost all of the upward field-aligned current in the arc is closed by local downward field-aligned currents, which leads to a closed current system in the vicinity of the polar cap arc. These results can now be used to model the global ionosphere including mesoscale structure, such as sun-aligned polar cap arcs.

Ionosphere – Magnetosphere Coupling → Polar Wind

The ‘classical’ polar wind is an ambipolar outflow of thermal plasma from the terrestrial ionosphere at high latitudes. The outflow, which can consist of H^+ , He^+ , and O^+ , begins at about 800 km. As the ionospheric ions flow up and out of the topside ionosphere along diverging geomagnetic field lines, they are accelerated and eventually become supersonic (above about 1300 km). As part of our SPTP research, we are studying several aspects of the polar wind, including its stability, 3-dimensional structure, outflow features during magnetic storms, and flow characteristics in the collision-dominated to collisionless transition region. We are also developing advanced time-dependent polar wind models. During the last six months, we completed papers dealing with both the polar wind transition region and advanced time-dependent models, and these results will be highlighted below.

As part of his Ph.D. dissertation, Pierre-Louis Blelly developed several advanced, time-dependent models of the polar wind. Specifically, Pierre-Louis used a flux-corrected-transport (FCT) numerical technique to solve *different sets* of generalized transport equations, including the Maxwellian based 5-moment (standard hydrodynamic equations), 8-moment, and 13-moment equations as well as the bi-Maxwellian based 16-moment transport equations. The latter sets (Maxwellian 13-moment and bi-Maxwellian 16-moment) have the advantage that temperature anisotropies and collisionless heat flow characteristics are included. The time-dependent models were then used for similar polar wind expansion scenarios in order to compare the model predictions and thereby determine which formulation is most appropriate for time-dependent applications.

In the polar wind simulations, a perturbation was created in a steady-state flow and then the temporal evolution of the ions (O^+ and H^+) and electrons was followed using the different sets of generalized transport equations. The results for the steady-state flow are shown in Figure 2 for H^+ . One general conclusion to be drawn from the study is that a much better representation of the polar wind is achieved with the more advanced transport equations because they take account of temperature anisotropies and asymmetric heat flows. However, an encouraging feature to note is that the 8-, 13-, and 16-moment formulations predict very similar results for the lower-order (density and drift velocity) moments. Therefore, the relatively simple, *three-dimensional* polar wind model that we

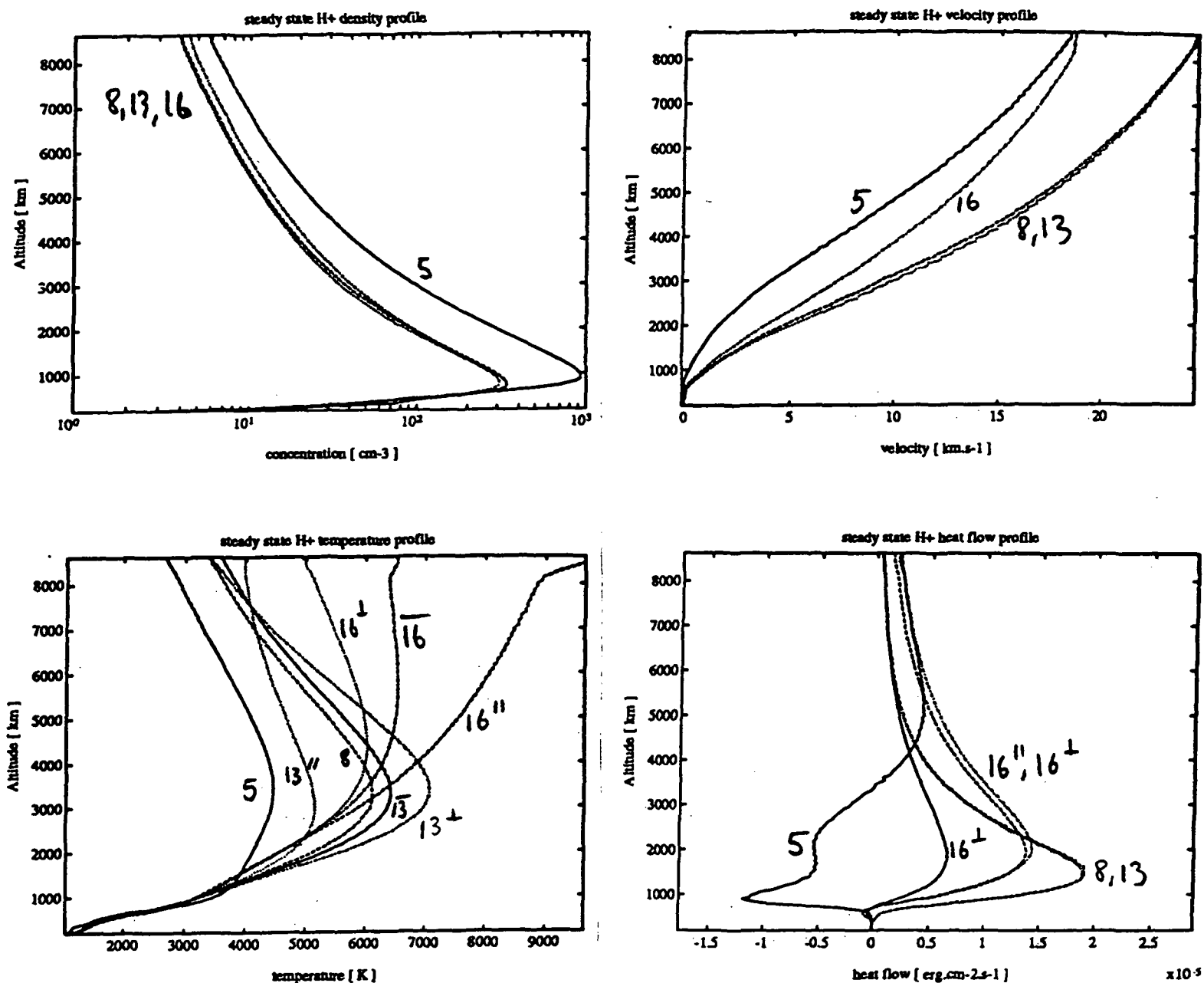


Fig. 2. Comparison of different transport model predictions for H⁺ ions in the steady-state polar wind. The 5-, 8-, 13- and 16-moment predictions are shown for the H⁺ density (top left), drift velocity (top right), parallel and perpendicular temperatures (bottom left), and heat flows for parallel and perpendicular thermal energies (bottom right). From paper 33.

developed does properly describe the density and drift velocity behavior in the polar wind. However, the advanced models do provide additional information and Figure 2 clearly indicates that the different models predict different temperature anisotropies and heat flows, with the 16-moment set of transport equations yielding the most reliable predictions.

As part of another Ph.D. dissertation, Imad Barghouthi used a Monte Carlo simulation technique to study the steady-state flow of the polar wind protons through a background of O^+ ions. The simulation region included a collision-dominated region (barosphere), a collisionless region (exosphere), and the transition layer embedded between these two regions. Special attention was given to using an accurate collision model, i.e., the Fokker-Planck expression was used to represent $H^+ - O^+$ collisions. The model also included the effects of gravity, the polarization electric field, and the divergence of the geomagnetic field. For each simulation, 10^5 particles were monitored, and the collected data were used to calculate the H^+ velocity distribution function f_{H^+} , the density, the drift velocity, the parallel and perpendicular temperatures, and the heat fluxes for parallel and perpendicular energies at different altitudes. From the study a number of interesting results were obtained. First, as shown in Figure 3, the shape of the H^+ velocity distribution function is very close to a slowly drifting Maxwellian in the barosphere, while a 'kidney bean' shape prevails in the exosphere. In the transition region, the shape of f_{H^+} changes in a complicated and rapid manner from Maxwellian to kidney bean. Second, the flow changes from subsonic (in the barosphere) to supersonic (in the exosphere) within the transition region. Third, the H^+ parallel and perpendicular temperatures increase with altitude in the barosphere due to frictional heating, while they decrease with altitude in the exosphere due to adiabatic cooling. Both temperatures reach their maximum values in the transition region. Fourth, the heat fluxes of the parallel and perpendicular energies are positive and increase with altitude in the barosphere, and they change rapidly from their maximum (positive) values to their minimum (negative) values within the transition region.

The results of this simulation were compared with those found in previous work in which a simple (Maxwell-molecule) collision model was adopted. It was found that the choice of the collision model can alter the results significantly. In particular, it affects the shape of the distribution function, especially in the transition region. It was also found to affect the relatively higher-order moments (heat fluxes) more than the lower-order ones (density, drift velocity, temperature). This indicates that rigorous (i.e., Coulomb) collision terms must be used in both polar and solar wind modelling if reliable temperature anisotropies and heat flows are desired.

Ionosphere - Magnetosphere Coupling → Convection Vortices

Convection electric fields have a dramatic effect on the ionosphere. As the ions drift through the neutrals, they are frictionally heated, which raises the ion temperature. The elevated T_i 's then act to increase T_e , and the elevated temperatures change the plasma densities via scale height changes in the topside ionosphere and temperature-dependent chemical reaction rates in the bottomside. Also, the ion velocity distributions (NO^+ , O_2^+ , N_2^+ , O^+) become non-Maxwellian in the regions of high electric field strengths. As the electric field increases, the ion velocity distribution evolves from a drifting Maxwellian, to a drifting bi-Maxwellian with $T_{\perp} > T_{\parallel}$, to a drifting toroidal distribution.

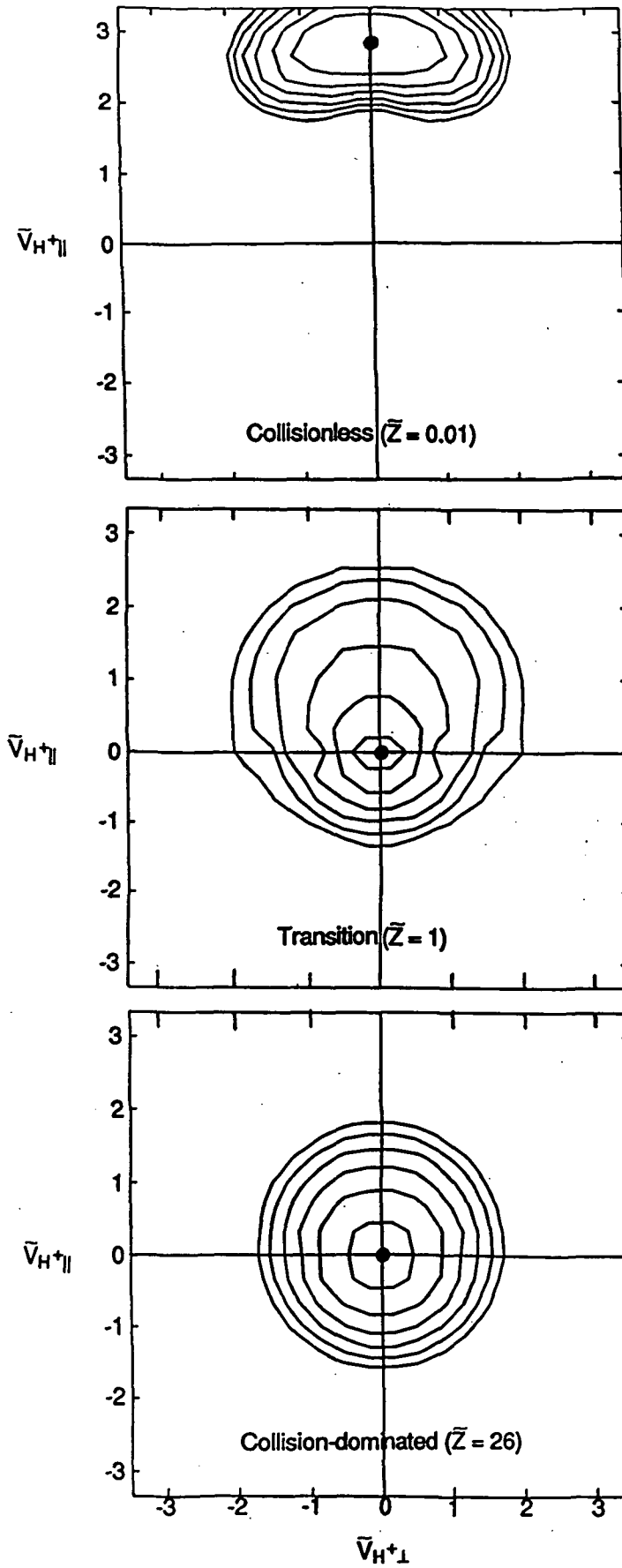


Fig. 3. Contours of the H^+ velocity distribution function in the barosphere (bottom), in the transition region (middle), and in the exosphere (top). The contour levels decrease successively by a factor of $e^{1/2}$ from the maximum, which is marked by a dot. From paper 31.

During the last decade, we have conducted numerous studies of the effect that empirical (large-scale, statistical) convection models have on the ionosphere, such as those developed by Volland, Heelis, Heppner and Maynard, and Foster. However, as noted earlier, the magnetospheric electric field pattern exhibits a considerable amount of mesoscale structure. A particularly interesting feature that was observed recently was *travelling twin convection vortices* embedded in a large-scale background convection pattern. The convection vortices were observed both near the dayside cusp and in the evening Harang discontinuity region. As the plasma rapidly convects around in these twin cells, there should be significant ion temperature enhancements, major ion composition changes, and highly non-Maxwellian velocity distributions. However, in order to model the effect on the ionosphere of such a convection feature, a model is needed for the twin convection cells themselves.

We are presently developing a self-consistent electrodynamic model to describe convection vortices. A possible physical picture of travelling vortices is described as follows. An increase in the solar wind velocity can trigger a K-H instability in the low latitude boundary layer, thereby producing a vortex. A filament of upward field-aligned current is associated with the vortex. We found, using our M-I coupling model, that when an intense, small-scale, upward field-aligned current filament connects to the ionosphere, an intense downward field-aligned current filament forms nearby in a short time. Therefore, the pair structure of travelling vortices appears to be a consequence of M-I coupling. Since the solar wind blows toward the magnetospheric tail, the vortices in the ionosphere move toward the nightside. Due to the decreasing velocity gradient as the vortex moves tailward, the K-H instability should dissipate and the convection vortices in the ionosphere should vanish on the nightside. The above qualitative picture is currently being quantified and tested using a two-dimensional MHD model.

Ionosphere - Plasmasphere Coupling

Although plasmaspheric dynamics has been studied for more than two decades, there are still several important unresolved issues. One of the issues concerns the loss of plasma from the plasmasphere. Currently, it is well-known that during magnetic storms and substorms, enhanced magnetospheric electric fields act to peel away the outer plasmasphere, and then this region refills via ionospheric upflows after the storms subside. However, we recently postulated the existence of an additional plasmaspheric loss mechanism that is associated with an azimuthal electric field component, which has not been considered before (paper 32).

Following MHD theories of magnetospheric convection, thermal plasma elements circulate along streamlines that are parallel to the equipotential surfaces of the electric field. The equipotential surfaces of magnetospheric convection electric field models were designed by combining a corotation electric field of ionospheric origin with a solar wind induced E field having a predominant dawn-to-dusk component. One of the most recent magnetospheric convection electric field models is shown in Figure 4a. This type of electric field generally has a stagnation point in the dusk local time sector. The Last Closed Equipotential line passing through this point of singularity was often used to identify the position of the plasmopause, or was used as an initial boundary condition for time-dependent computer simulations of the motion of the plasmopause surface during disturbed

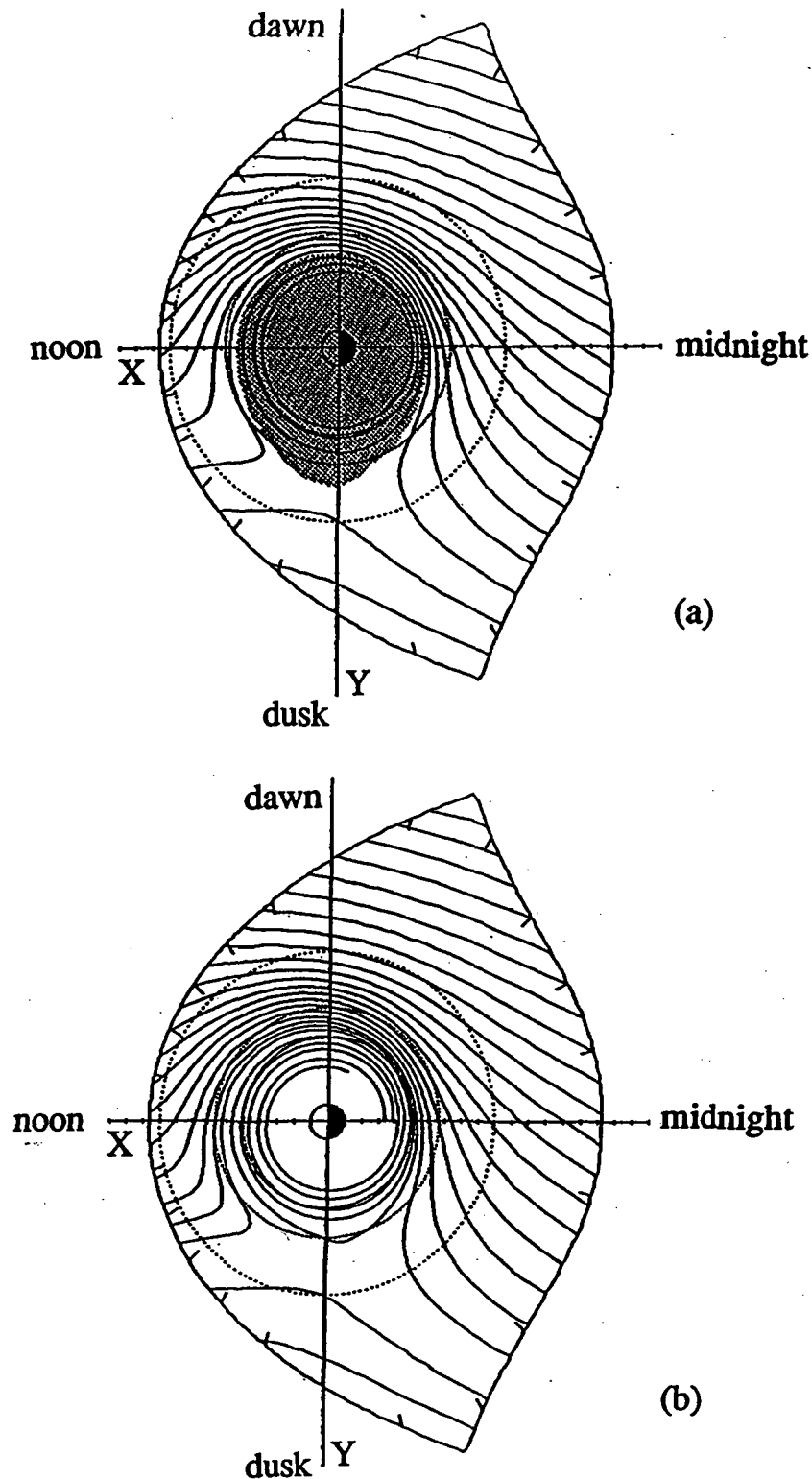


Fig. 4. (Panel a) Equatorial cross-section of the magnetosphere showing equipotential lines corresponding to the convection electric field model E5D of McIlwain. Note that this steady state E field model has a dawn-dusk asymmetry and a stagnation point near 1800 LT, which are characteristic of most of the earlier magnetospheric convection electric field models. (Panel b) This electric field distribution is the same as the model E5D, except that a small azimuthal dc E field component (E_ϕ) has been added in the eastward direction. This additional poloidal field is such that the mean radial drift velocity has a constant outward $E \times B/B^2$ component; it corresponds to a constant radial plasmaspheric wind of 106 m/s ($0.06 R_E/h$). From paper 32.

geomagnetic conditions. The shaded region bounded by this Last Closed Equipotential was then considered to be the equatorial cross-section of the plasmasphere. In this case, under steady state conditions, none of the plasma elements circulating inside this shaded region are convected away from the Earth and out of the plasmasphere. For these earlier models the average azimuthal component E_ϕ was assumed to be zero, i.e., any contour integral around the Earth of E_ϕ was postulated to be equal to zero: $\oint E_\phi \cdot dl = 0$. However, there is no compelling reason to assume that the distribution of electric fields in the magnetosphere satisfies the restrictive condition of $\oint E_\phi \cdot dl = 0$. There are, indeed, more general magnetospheric E field configurations, like that shown in Figure 4b, which are not based on such an "a priori" assumption. For the model shown in these figures, $\oint E_\phi \cdot dl = Cst \neq 0$. The consequence of a non-zero azimuthal electric field component is that all thermal plasma elements, even those deep inside the plasmasphere, are now able to move outwards along spiral drift paths and eventually they will end up at the magnetopause surface where they are lost. We estimate that this new loss mechanism corresponds to an outward flux of about $3 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ for both ions and electrons. When integrated over the entire plasmasphere, this loss mechanism is very substantial.

Validity of Macroscopic Plasma Flow Models

Numerous mathematical formulations have been used over the years to describe plasma flows in the solar-terrestrial environment, including Monte Carlo, hybrid particle-in-cell (PIC), kinetic, semikinetic, hydromagnetic, generalized transport, and hydrodynamic formulations. All of these formulations have both strengths and limitations when applied to macroscopic plasma flows. For example, the transport formulations (hydromagnetic, generalized transport, and hydrodynamic) can describe multispecies flows, multistream flows, subsonic and supersonic flows, collision-dominated and collisionless regimes, chemically-reactive flows, and flows that are characterized by highly non-Maxwellian conditions (generalized transport equations). Typically, these formulations can also be extended to multi-dimensions. They are limited, however, in that they are obtained by truncating the infinite hierarchy of moment equations and, in general, it is not clear how the truncation affects the solution. The kinetic and semikinetic models are particularly suited to collisionless, steady-state plasma flows. They have an advantage in that the full hierarchy of moment equations are implicit in the solution and multiple particle populations can be readily included. Some of their limitations are that they are difficult to apply to time-dependent, multi-dimensional or collisional flows and, as a consequence of the latter, an artificial discontinuity can occur at the boundary. Monte Carlo and PIC techniques have the advantage that you follow the motion of individual particles and, hence, a lot of the important physics can be included self-consistently. Monte Carlo techniques are particularly useful for collision-dominated gases, and with the PIC approach, self-consistent electric fields can be easily taken into account. Some disadvantages are that both techniques are computationally demanding and, therefore, they cannot be easily extended to multi-dimensional situations. Also, when PIC techniques are applied to macroscopic flows, "macroparticles" are used, and this introduces numerical noise, which can significantly affect the resulting physics. Specifically, the random scattering of particles due to numerical noise can significantly reduce temperature and heat flow anisotropies in an artificial manner.

In an effort to more fully elucidate the validity of the various plasma flow formulations, we conducted a systematic comparison of several of the formulations for the same plasma flow conditions. We also attempted to elucidate some of the limitations associated with a given mathematical formulation so that the detrimental effects associated with the limitations can be minimized. During the last six months, we completed a paper in which we compared generalized transport and Monte Carlo models that mathematically describe the escape of a minor species from the upper atmosphere (paper 20). The models were compared over an altitude range that went from collision-dominated to collisionless flow conditions. In general, the two models were in very good agreement with regard to their predictions for the physically significant velocity moments (density, drift velocity, temperatures, etc.). Good agreement was obtained not only in the collision-dominated regime, but in the transition region and collisionless regime as well. Figure 5 shows the comparison of the Monte Carlo and 16-moment transport theory predictions for the minor species density, parallel (to **B**) temperature, and the heat flow for parallel thermal energy. The good agreement between the two approaches for this problem provides further evidence that the 16-moment set of generalized transport equations is a powerful tool for studying many space physics problems.

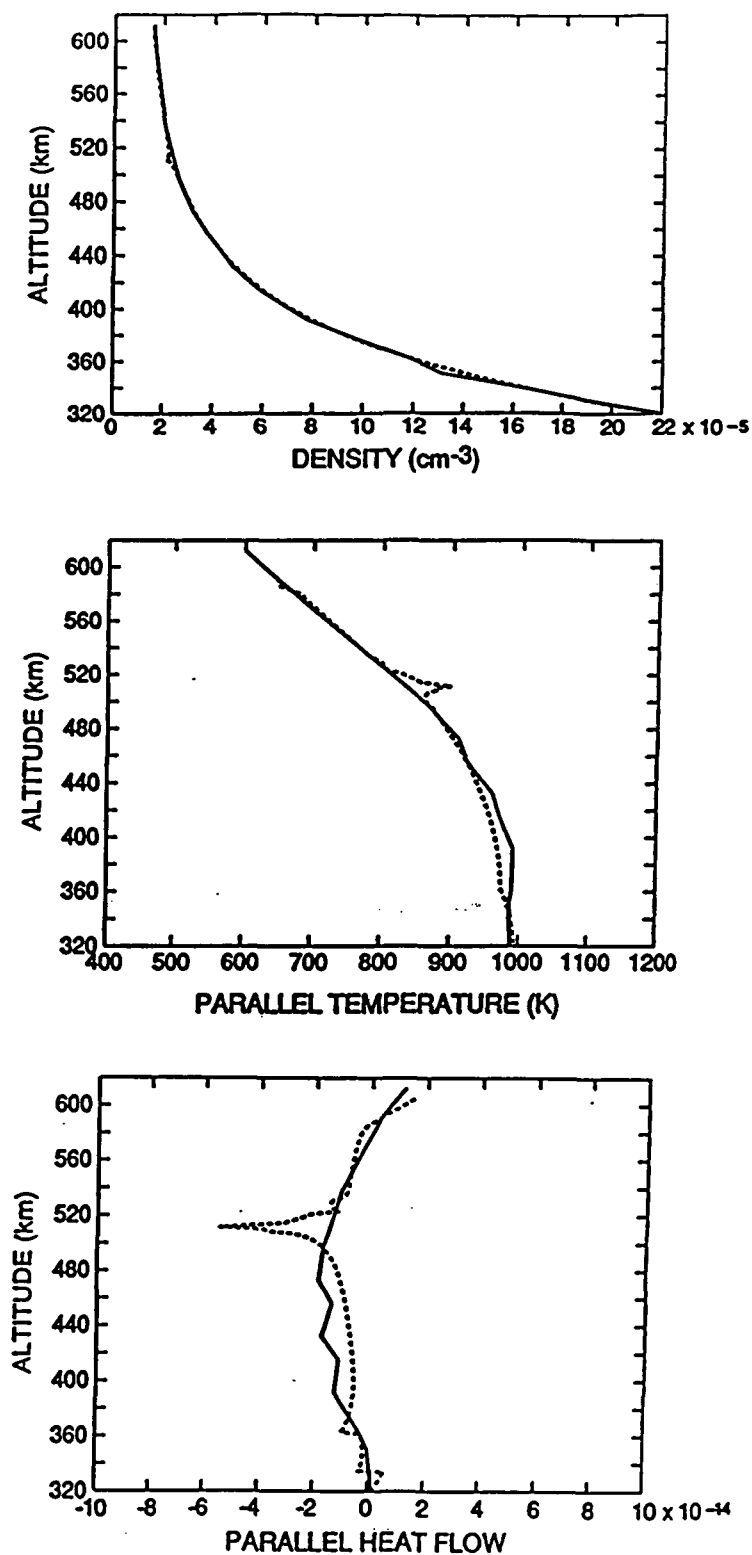


Fig. 5. Comparison of the Monte Carlo (solid curves) and 16-moment transport (dashed curves) profiles for the minor species density, parallel temperature, and heat flow for parallel thermal energy. The level of agreement between the results degrades slightly as the order of the velocity moments being compared increases. From paper 20.

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